

SIMULATING F-22 HEAVY MAINTENANCE AND MODIFICATIONS WORKFORCE MULTI-SKILLING

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ABSTRACT

The U.S. Air Force aircraft maintenance depots face complex operating environments due to the diversity of aircraft or mission design series (MDS) maintained by each depot and the variability of maintenance requirements for each MDS. Further complicating their operations is the variability of maintenance actions required from one aircraft to another within each MDS and a highly specialized workforce that has inherent inflexibility to compensate for the workload variability. Air Force Materiel Command is reviewing maintenance personnel multi-skilling as a method to efficiently absorb the variability of workload and maintenance requirements between aircraft. Using a simulation built in ARENA 14®, we studied the F-22 Heavy Maintenance Modification Program through a series of designed experiments. Our study analyzes whether using a multi-skilled workforce impacts the productivity of depot maintenance personnel through simulation of several multi-skilling policies.

1 INTRODUCTION

The Air Force faces significant fiscal challenges in the coming years with dwindling defense budgets and increasing procurement and sustainability costs associated with more technologically advanced weapons systems and an aging legacy fleet. The Air Force Sustainment Center and the three Air Logistics Complexes (ALCs) under their purview are at the forefront of the battle to affect the cost curve for sustainment operations. The aircraft maintenance depot activities at Ogden ALC, Oklahoma City ALC and Warner-Robins ALC face complex operating environments due to the diversity of aircraft or mission design series (MDS) maintained by each depot and the variability of maintenance requirements for each MDS. Further complicating their operations is the variability of maintenance actions required from one aircraft to another within each MDS and a highly specialized workforce that has inherent inflexibility to compensate for the workload variability.

Multi-skilling is one proposal that Air Force Materiel Command (AFMC) is reviewing to absorb the variability of workload and maintenance requirements between aircraft. Multi-skilling is defined as “a position that combines two or more journeyman, full performance or higher level skills in the same pay plan in which formal on-the-job or classroom training is required” (Federal Service Impasse Panel 1997). In 1993 the Oklahoma City ALC implemented a multi-skill program, but the program never materialized in the way designed and therefore had negligible results. The question remained unanswered on whether Air Force depot operations can more cost effectively use their work force through multi-skilling.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE DEC 2014		2. REPORT TYPE		3. DATES COVERED 00-00-2014 to 00-00-2014	
4. TITLE AND SUBTITLE Simulating F-22 Heavy Maintenance and Modifications Workforce Multi-skilling				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology, Department of Operational Sciences, 2950 Hobson Way, Bldg 641, Wright-Patterson AFB, OH, 45433				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Proceedings of the 2014 Winter Simulation Conference, 7-10 Dec 2014, Savannah, GA.					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

For that reason, AFMC requested an analysis of the F-22 Heavy Maintenance and Modification Program to estimate the potential benefits of a multi-skilled workforce.

We begin by introducing the problems attributed to a task centric maintenance workforce within the F-22 Heavy Maintenance Modification Program. We then discuss modeling the F-22 depot maintenance process and our verification and validation process. Finally we present the results of our study and provide recommendation for future research.

2 PROBLEM DEFINITION

The F-22 Heavy Maintenance Modification Program consists of several Federal Wage Series occupations that perform maintenance on the F-22 depot production line. However, the F-22 depot is currently experiencing indirect labor hours and overtime rates above their target levels in their “current state” operations today. They are furthermore concerned that their overtime costs may increase in a planned “future state” when required annual aircraft throughput will increase. A business case analysis completed by Ogden ALC in 2012 hypothesizes that the problems lies in the Painter (Low Observable or LO) workforce constraints and associated downtime of other occupations awaiting LO task completion.

The cost associated with overtime and idle personnel created by the painter labor-hour constraint appears to create an opportunity for potential productivity gains by multi-skilling other labor specialties to increase painter labor hours availability. No substantive quantitative analysis exists on which maintenance specialties within F-22 depot operations are favorable for multi-skilling into the painter specialty. Additionally, no quantitative analysis exists to estimate the aircraft throughput and employee utilization impacts of multi-skilling in depot operations other than a limited simulation of the KC-135 depot process by Levien (2010).

3 LITERATURE REVIEW

3.1 Simulation

The complexity of the F-22 Heavy Maintenance Modification Program and the AFMC desire to review multiple multi-skilling policies led us to select simulation to model the system. Banks et al. (2010) explain that many real-world systems are so complex that models of the systems are virtually impossible to solve mathematically and simulation allows for the study of those systems. Law (2007) notes that it is rarely necessary to include every element of the system in the model in order to make effective decisions, and in some cases can cause excessive model run time, causing missed deadlines and obscuring important factors. Including the relevant details in the model facilitates the ability of the model to provided system insights that are useful for decision making.

The reasons for using simulation can be negated if the model does not reflect real system behaviors or if the outputs do not provide useful insights into system behaviors. Deliberate verification and validation (V & V) ensures the model reasonably depicts the real system and its associated behaviors. Carson (2005), Law (2007), Banks et al. (2010), and Little (2004) emphasize the importance of involving managers and their teams in validating the model. We did this with two trips to the depot and with periodic telephone calls and email exchanges with the depot team.

3.2 Depot Maintenance and Multi-skilling Simulation

Levien (2010) simulated the KC-135 depot maintenance process, focusing specifically on whether multi-skilling improved a designated major job within the process. He considered only three of the six maintenance specialties used in the major job tasks. Model validation proved quite difficult for him—possibly because he was only able to model a portion of the aircraft repair network. He was still able to provide interesting insights on multi-skilling personnel that helped us to focus our work.

Park (1991) examined cross-training in a dual resource constrained shop. He studied dual resource constrained systems, where both personnel and resources were needed to complete a job but excess machines exist. He used a SLAM simulation to model five work centers at varying levels of cross-trained

personnel and with differing work dispatch policies, and concluded that “The minimum introduction of worker cross-training showed the most significant improvement, and subsequent increase in cross-training had diminishing return”. His results support the business case analysis completed by the Ogden ALC in 2012.

3.3 Marginal Analysis

The objective of our research was to investigate whether multi-skilling personnel policies could provide better flowtime and cost outcomes than the status quo overtime policy. Marginal analysis is a form of optimization that assists in selecting from among differing technically efficient alternatives (de Neufville, 1990). Marginal analysis is useful for investigating the system design through simulation if the costs of inputs are readily available and allows for selection of the alternative that gives the best return on inputs invested. Ysebaert (2011) used marginal analysis by implementing a “shopping list” approach to gauge the improvements of Adjusted Stock Level panels for the F-22. Her marginal analysis measured aircraft availability improvement versus the cost of an additional panel. Ysebaert’s results provided valuable insights into the aircraft availability improvements possible with purchases of additional panels as well as the cost of those improvements. Similar methods are used in the Aircraft Sustainability Model by comparing optimal spares mixes based on a target metric defined by the user (Slay et al. 1996). Both Ysebaert (2011) and Slay et al. (1996) use marginal analysis based on simulation outputs to decide the “benefit per dollar”, where the scenarios with the highest benefit should be at the top of the “shopping list”.

For our system, the goal is not just to compare alternatives but also to select the best of the differing alternatives through statistically proven ranking-and-selection (R & S) methods. Kim and Nelson (2006) give four comparison problems that arise in simulation studies including comparing alternatives against a standard, selecting the best performing system, selecting the system with the highest probability of performing the best, and selecting the largest probability of success. Their emphasis is on the constraint applied to probability of the correct selection (Kim and Nelson, 2006). Nelson et al. (2001) offer procedures for selecting the best system and experimental results that validate its ability to find the best system with a confidence level of at least $1-\alpha$. Banks et al. (2010) provide an automated tool that implements these procedures in the SimulationTools.xls spreadsheet at www.bcnnet.net.

4 METHODOLOGY

4.1 Goal and System of Interest

Our goal was to quantitatively examine multi-skilling and gain insight into specialty selection for multi-skilling. We built a simulation in ARENA 14® with outputs capturing aircraft throughput, average flow days, employee utilization by specialty, and dock usage. Prior to delving into the details of the model, we briefly discuss the system of interest and the model scope.

The entity of primary interest is individual aircraft that enter and exit the system. Aircraft must be periodically inspected and overhauled at a depot. The system boundaries for our research are defined as starting when depot maintenance personnel begin scheduled maintenance actions on an aircraft and as stopping when all maintenance actions are complete. Each aircraft arrives at scheduled intervals determined by engineering specifications and based on collaborative planning between the aircraft depot planners and organizations that own the aircraft. Each aircraft arrives with a preplanned number of maintenance actions scheduled based on modifications required, the delayed discrepancies identified for completion and any other maintenance requirements found during the depot process. The aircraft is scheduled to be in the system for a predetermined number of workdays based on maintenance man-hour requirements with all maintenance actions scheduled for completion within this time frame. The planned flow days for each aircraft are broken down into seven measureable segments referred to as gates. The seven gates exist as milestones within the process to focus maintenance efforts on meeting predetermined timelines and goals for process completion. Management and production supervisors restrict personnel to

working only maintenance actions required within the gate the aircraft is currently assigned and maintenance actions within the next gate do not begin until all actions from the previous gate are completed, with rare exceptions. There are six Federal Wage Series (FWS) occupational specialties that complete a majority of the maintenance activities within each of the seven gates. A critical path analysis by the depot planners identified maintenance activities of these six specialties as critical path tasks and focused our research efforts on the six identified specialties.

4.2 Model Scope and Inputs

We initially considered modeling only a few of the seven gates to manage the model size and complexity. Modeling two or three gates will give an idea of output behaviors associated with those gates as multi-skilling is implemented and may give an accurate representation of the overall system behaviors associated with multi-skilling. The problem with this approach is that man-hour requirements per specialty vary greatly between each gate and isolating the model to certain gates may inaccurately show higher manpower availability than actually exists within the entire system if the wrong gates are included. Further complicating the problem of identifying gates for inclusion is that subject matter expert inputs identify periods when excess resource (personnel) capacity exists due to inactivity in a gate (i.e. no aircraft in the gate). Management and planners seem unable to forecast the gates and periods when this excess capacity will arise, leading to our decision to model all seven gates versus scoping the model to a few. After deciding to model the entire system, our next step was to decide on the level of detail to include within the model.

The highest level of detail is to model the system at task level in order to most accurately capture the benefits of multi-skilling. However, our time constraints, the sheer number of maintenance tasks (three to four thousand) required on each aircraft, and the variability of the number of tasks from one aircraft to the next make modeling all tasks impractical for this study. Since variability of man-hour requirements is the most significant challenge that multi-skilling is proposed to address, the key factor in determining the level of aggregation for the model is the ability to simulate multiple types of aircraft from a man-hour requirement perspective. With this in mind, we identified the data that managers and planners use to forecast current requirements. F-22 depot planners had already worked with a team from Clemson University to produce an automated scheduling tool to identify man-hour requirements per specialty per day. The Clemson tool produces the aggregate man-hour requirements per specialty per flow day for an aircraft as well as other scheduling outputs. The tool pulls data from the depot's Programmed Depot Maintenance Scheduling System, including the standard forecast hours based on the projected maintenance requirements of an aircraft or the actual hours used to complete an aircraft previously in the system. Most decisions within depot operations are viewed from the man-hour requirement perspective and so we designed our simulation model to incorporate that paradigm by using the Clemson tool inputs. Therefore, the model was built with the intent of simulating the flow of aircraft through the system with maintenance actions on each aircraft being performed based on man-hour requirements for each of the six specialties per day.

4.3 Model Description

The ARENA 14® simulation was built to reflect the depot system of interest in two states, the current and projected future state of the system. The two models are identical with only minor input differences based on changes in projected workloads and personnel resources available.

The aircraft arrive at constant intervals to reflect the flow rate required to reach target aircraft throughput for each year. Upon arrival, the aircraft flows through eight main sub-models including a Characteristics sub-model and additional sub-models for each of the 7 Gates as depicted in the top of Figure 1.

The Characteristics sub-model randomly decides which of four possible types of aircraft are arriving using probabilities based on depot data. Each aircraft type represents a different level of required maintenance activity and is based on four actual aircraft histories: one with a minor amount of required work; one with a large amount of required work, and two others that represented intermediate levels of required

work. The random selection of the four types of aircraft induces man-hour requirement variability into the system and is a critical factor to accurately reflect the variability of real system inputs. The Characteristics sub-model also “deconflicts” arrivals based on the constraint to have only a certain number of aircraft within the system at any time. After exiting the Characteristics sub-model, the aircraft is considered to be work in process and enters Gate 1.

The Gate 1 sub-model is broken down into six main processes and two main lower-tier sub-models with several record functions used to tally statistics throughout the gate. The aircraft is separated into six different entities as shown between points A and B in Figure 1. The entities flow into separate paths representing the six FWS specialties of interest. In queuing theory terms, each path corresponds to a different type of server required to complete a specific maintenance activity. Using a different path design allows resource pooling based on the type of server. When multi-skilling is introduced the server is able to complete maintenance hours associated with multiple resource pools versus just one. The paths are replicas of each other with minor equation differences.

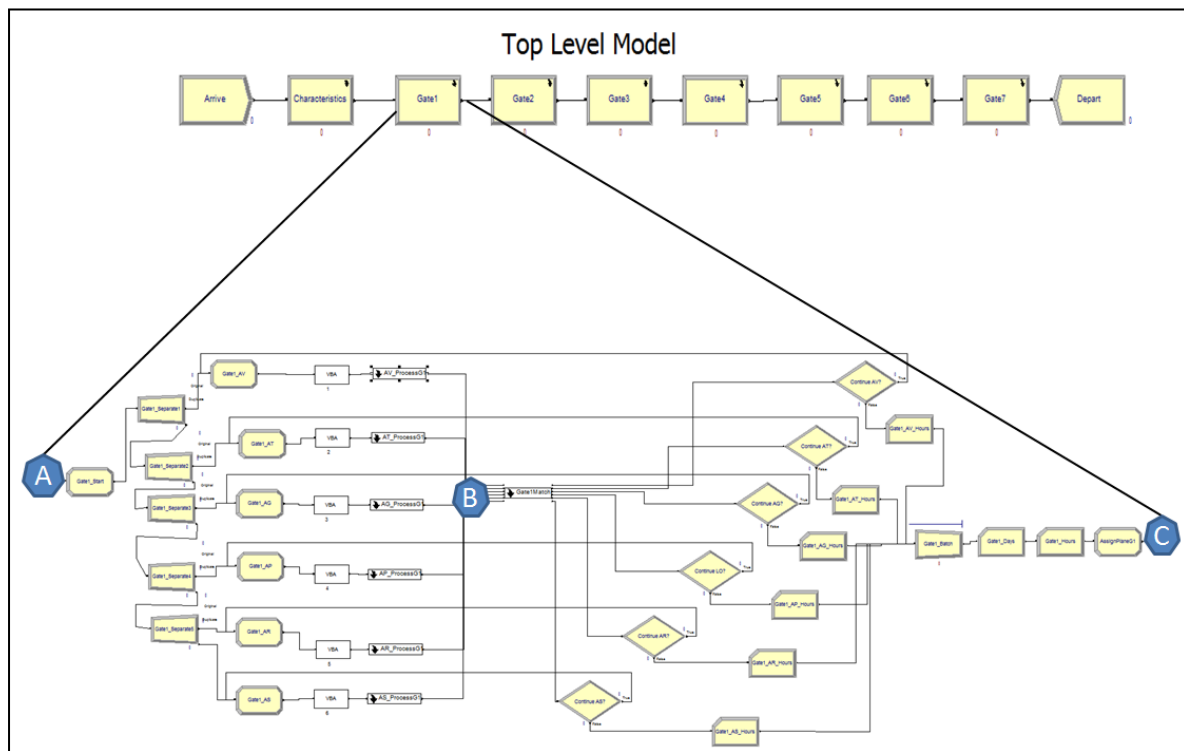


Figure 1: Top level model – Gate 1 sub-model.

Each path contains a Visual Basic block that uses custom code to read in the specialty’s daily maintenance hour requirements from the Clemson scheduling tool. The maintenance hour requirements are assigned based on the type of plane assigned and the aircraft’s current flow day. Then the aircraft flows through a sub-model that decides the number of personnel to seize by a subsequent process module. The process module uses resource sets to seize personnel. Each resource set contains the primary maintenance specialty required and a multi-skilled specialty for each of the other five specialties paired with the primary specialty. The personnel resources are seized until the hourly requirements are met for the day based on the hourly requirement divided by the number of personnel seized.

Once maintenance requirements are met, the second half of the gate (Figure 1, points B to C) restrains the six identical entities to remain within a certain number of flow days of each other. It then re-loops the entities back to the beginning of the gate if the entity requires more flow days within the gate and batches the entities back into a single aircraft before allowing it to exit the current gate. When all re-

quirements are met for each of the seven gates the flow days and other output statistics are recorded and the aircraft exits the system.

The depot operates today on a three-shift schedule. We set the personnel capacity for each specialty to the value of one shift of personnel. The model's hours-per-day value was adjusted to reflect the duration of three shifts worth of labor hours, mimicking the number of hours that personnel would be available to complete maintenance in a given day. This method reflects the same personnel and labor hours available as scheduling three equal personnel, equal duration shifts. The only difference is the shift change is removed and the personnel continue on the job instead of instantaneously stopping maintenance, changing personnel, and restarting the same maintenance (processing) with the same type of person or resource.

4.4 Model Verification and Validation

Verification and validation of a simulation model ensures the design and function accurately represents the behaviors of the real system. According to Carson (2005), "The result of the V & V phase is a verified, validated model that is judged to be accurate enough for experimentation purposes over the range of system designs contemplated". For this reason, we built the simulation model in a piecewise fashion with verification and validation methods being used continually throughout the process. Final validation of the model included comparison with historical data and discussions with depot subject matter experts. The simulation produced outputs within 2 percent of the expected values from historical data, which we deemed satisfactory.

The warm-up period is 100 days for the current state in order to load work-in-process (WIP) aircraft into the model and to allow enough time for the first aircraft to exit the system at the start of statistics collection. The future-state warm-up period is 200 days. Our reasoning for allowing the first aircraft to exit the system is that personnel resource constraints do not affect the WIP aircraft until a truly representative quantity of aircraft are in the model, which enables the first aircraft to flow through the system at an unrealistic rate with seemingly minimal resource constraints. The warm-up period is added to the replication run length.

We used the flow days coefficient of variation (CV) to determine run length and number of replications, by varying the run length from 3 to 10 years and replications from 5 to 30. We found that 15 replications of 10-year run lengths per scenario provided the best tradeoff of acceptable run times versus output variation.

4.5 Experimentation

We used marginal analysis together with the Select-the-Best Procedure from Banks et al. (2010). The Select-the-Best Procedure was used to select the scenario with the best improvement over the baseline using a 95 percent confidence level and an indifference level of two days. Our "current state" experiments include a personnel-add experiment and several multi-skilling policy experiments. The "future state" experiments include a personnel reduction experiment and reduced workforce multi-skilling experiments.

The first current state experiment mimics adding overtime through the addition of personnel and the same method is used in the future state experiments to re-add personnel. We add one person by specialty for each run, reflecting the addition of three additional personnel per day or one person in each of the three balanced shifts (1800 labor hours/person/year). Each experimental level contains six runs; one run (scenario) for each specialty. Note that only one specialty has added personnel from the baseline for each run. The specialty that shows the most improvement in flow days from the additional personnel using the Select-the-Best Procedure is retained as the new baseline for the next comparison. This method of marginal analysis is similar to Ysebaert's (2011) "shopping list" method but uses the Select-the-Best Procedure to choose the best system. The current state experiment shows the impact of adding personnel (overtime hours) on flow days and provides a comparison for multi-skilling improvements.

The multi-skilling experiments consider different multi-skilling policies by altering the maintenance specialty processes that a set of personnel (a particular specialty) within the system can complete. Then

the personnel add and multi-skilling experiment results are compared to identify the policy with the best system performance. The personnel add and multi-skilling methods are similar in both our current and future state experiments. The multi-skilling experiments consider pairings proposed in the 2012 Ogden ALC business case analysis and pairings selected based on utilization rates and resource capacity.

5 RESULTS AND ANALYSIS

We discuss our results for both the system current and future states. Note that the principal difference between the current state and the planned future state systems are increases in workload, personnel resources, and changes in the percentages for the types of aircraft arriving.

5.1 Current State Results

The current state experiments reflect the depot's throughput today and provide a comparison between overtime use and multi-skilling different number of personnel. Table 1 shows that multi-skilling a workforce using targeted (experiment treatments that build on insights from prior model runs) multi-skilling policies with no efficiency losses enable aircraft throughput similar to the best overtime scenario. Our cost figures use 2012 rates for overtime or an additional \$2.03 hourly wage rate for multi-skilled personnel. The annual cost difference between the best targeted multi-skilling policy (Level C1) and overtime policy (Level A8) is approximately \$1,152,000. The second best targeted multi-skilling policy (Level C2) provides a two-flow-day difference from the best overtime result with an annual cost difference of \$1,349,000. Note that C1 and C2 are not statistically different from each other. In the two best targeted multi-skilling experiment levels, the flow day outputs show a 12 to 13 percent decrease in flow days from the baseline model, falling 2 to 3 percent below the flow day target (goal) for the system.

Table 1: Current state results summary.

Current State Experiments - Results Summary					
Experiment Name (Level)	Flow Days	Delta w/Baseline	Annual Throughput	Overtime / Multi-skill Hrs	Annual Cost
Baseline	133.99	N/A	9.90	N/A	N/A
Personnel Add - Overtime (A8)	115.5	-18.5	11.30	48,600	\$1,965,870
Targeted Multi-skilling (C1)	116.29	-17.7	11.27	400,950	\$813,929
Targeted Multi-skilling (C2)	117.55	-16.4	11.14	303,750	\$616,613
Targeted 98% Efficient (C1)	119.8	-14.2	11.03	400,950	\$813,929
Targeted 98% Efficient (C2)	120.92	-13.1	10.87	303,750	\$616,613
Personnel Add - Overtime (A6)	120.96	-13.0	10.92	32,400	\$1,310,580
Targeted Multi-skilling 95% Efficient (C1)	123.16	-10.8	10.77	400,950	\$813,929
Personnel Add - Overtime (A4)	123.54	-10.5	10.67	21,600	\$873,720
Targeted Multi-skilling 95% Efficient (C2)	124.9	-9.1	10.60	303,750	\$616,613
Personnel Add - Overtime (A3)	125.26	-8.7	10.58	16,200	\$655,290
Personnel Add - Overtime (A1)	129.82	-4.2	10.24	5,400	\$218,430
Targeted Multi-skilling 90% Efficient (C1)	130.22	-3.8	10.20	400,950	\$813,929
Targeted Multi-skilling 90% Efficient (C2)	131.25	-2.7	10.15	303,750	\$616,613
AP All Multi-skill 100% (B1)	135.12	1.1	9.70	400,950	\$813,929
Average Flow Day Target w/OT	120.64		Expected OT Cost for Real System		\$1,240,116

As workers become responsible for multiple skills, they risk a decline in individual skill proficiency. However, we found that reductions in efficiency levels to 98 percent (reflective of 2 percent longer processing times) for the targeted policies still provide aircraft throughput timelines that fall below the flow day goal with overtime. These policies indicate a cost difference between multi-skilling and overtime of \$694,000 annually for the targeted multi-skilling second-best policy and \$497,000 annually for the best performing policy, both at 98 percent efficiency. Further reducing the workforce efficiency level diminishes the cost differences between overtime and targeted multi-skilling with break-even points occurring at 95 percent efficiency for both targeted policies. This indicates that maintenance actions can take up to

5 percent longer before the overtime and multi-skilling policies become equally preferable in terms of cost. One point of interest is that the second best targeted multi-skilling experimental level includes 48 fewer multi-skilled personnel than the best policy. If efficiency losses occur, the impacts would be less under the policy with fewer multi-skilled personnel.

Overall, our results support the hypothesis of productivity increases and cost savings from multi-skilling policies proposed in the Ogden Air Logistics Complex's 2012 BCA. However, we found that multi-skilling all five of the non-painter FWS maintenance specialties into the painter skill, as prescribed by the BCA, is not a desirable policy in terms of flow day reductions, annual aircraft throughput, and cost.

5.2 Future State Results

The depot plans to accommodate their future state workload by doubling their current workforce staffing. We found that this plan would let them achieve their projected flow day goals, but at high labor cost. We therefore created a "trade space" by establishing a 15% smaller workforce as baseline for our experiments. A multi-skilling experiment was then conducted on the reduced workforce baseline and personnel were re-added to the best multi-skilled scenarios. The goal of this group of experiments was to determine whether targeted multi-skilling policies allow for a reduction in future maintenance personnel requirements. The future state results summary is displayed in Table 2.

Table 2: Future state results summary.

Future State Experiments- Results Summary						
Experiment Name (Level)	Flow Days	Delta w/ Target Flow Days	Annual Throughput	Multi-skilled Personnel	Total Personnel	Annual Cost
E9 Multi-skill Personnel Add Best (G7)	121.07	-4.5	22.04	257	357	\$25,806,296
E6 Multi-skill Personnel Add Best (F4)	121.89	-3.7	22.08	348	348	\$25,552,422
E9 Multi-skill Personnel Add (G6)	122.97	-2.6	21.86	255	354	\$25,586,017
E6 Multi-skill Personnel Add (F3)	123.16	-2.5	21.82	345	345	\$25,332,143
Baseline Model (No Reduction)	123.33	-2.3	21.81	0	396	\$27,449,037
E9 Multi-skill Personnel Add (G5)	123.65	-2.0	21.74	252	351	\$25,365,737
E9 Multi-skill Personnel Add Best (G7) 98% Efficient	124.47	-1.1	21.61	257	357	\$25,806,296
E6 Multi-skill Personnel Add Best (F4) 98% Efficient	124.75	-0.9	21.57	348	348	\$25,552,422
E9 Multi-skill Personnel Add Best (G7) 95% Efficient	128.31	2.7	21.02	257	357	\$25,806,296
E6 Multi-skill Personnel Add Best (F4) 95% Efficient	128.46	2.9	20.92	348	348	\$25,552,422
Personnel Reduction 5% (D1)	129.08	3.5	20.86	0	378	\$26,201,354
Personnel Reduction 10% (D2)	132.92	7.3	20.28	0	357	\$24,745,723
E6 Multi-skill Personnel Add Best (F4) 90% Efficient	135.5	9.9	19.88	348	348	\$25,552,422
E9 Multi-skill Personnel Add Best (G7) 90% Efficient	135.88	10.3	19.82	257	357	\$25,806,296
Average Flow Day Target w/Overtime	125.61					

The results show that multi-skilled workforce scenarios with no efficiency loss and between 39 and 51 fewer personnel produce results superior to the baseline model with no personnel reductions. Additionally, the second best multi-skilled experiment produces statistically equivalent flow day outputs to the baseline with a reduction in workforce of 51 personnel and a cost avoidance/savings of \$2,117,000 annually.

Even with a 2 percent increase in all daily maintenance processing times reflected by a less-efficient workforce, the best multi-skilled scenarios beat flow day goals by approximately 1 day. A 5 percent increase in all processing times misses the flow day target by 2.7 and 2.9 days. However, both scenarios provide a cost avoidance/savings of at least \$1,643,000 per year. The cost difference provides management flexibility to add overtime or personnel to compensate for the increased processing times. The experiments and analysis of the current and future state models provide valuable insights into the benefits associated with multi-skilling personnel within depot operations.

6 CONCLUSION

We show that in both current and future operational states for F-22 depot operations, targeted multi-skilling policies with no productivity losses increase aircraft throughput to levels exceeding the current overtime policies with significant cost savings/avoidance. Furthermore, our research shows that the best performing multi-skilling policies are cost favorable for a given level of aircraft throughput down to the 95 percent efficiency level. This means that multi-skilling is favorable up to the point that all required maintenance times grow by 5 percent due to productivity losses associated with a more generalized workforce. At that point, overtime and multi-skilling become cost equivalent with further processing time increases causing overtime to be more desirable.

Additionally, employee utilization and available labor hours improve significantly with multi-skilling, as is indicated by our experimental results showing significant improvements in aircraft flow day and throughput measures with a multi-skilled workforce. In both the current and future state experiments, a multi-skilled workforce provided more annual throughput and direct labor hour usage than a workforce of equal or greater size with no multi-skilling.

A limitation of our study is that the multi-skilling cost calculations did not include time considerations to obtain security clearances or additional training. Additionally, the aggregate level of data used drove us to make additional assumptions and create work-arounds. Finally, time constraints and lengthy model run time limited our analysis to marginal analysis with associated one factor-at-a-time adjustments, which do not give a full picture of the possible interactions and interdependencies of input variables and their impact on outputs.

We conclude by identifying opportunities for further research. Our first recommendation is to model future weapon system depot processes during the design phase to assess personnel requirements and potential multi-skilling levels and benefits. For these simulations, we recommend using software with more robust capabilities for resource related scheduling and seizing (possibly an agent-based or object oriented simulation tool). Finally, the Air Force should investigate methods for implementing a flexible (multi-skilled) workforce to decrease the impact of proficiency losses associated with skill generalization.

DISCLAIMER

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government.

REFERENCES

- Banks, J., Carson II S, J., Nelson L, B., & Nicol M, D. 2010. *Discrete-Event System Simulation*. 5th Edition. Upper Saddle River, New Jersey: Prentice-Hall, Inc.
- Carson II, J. S. 2005. "Introduction to Modeling and Simulation." In *Proceedings of the 2005 Winter Simulation Conference*, edited by M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, 16-23. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.
- de Neufville, R. 1990. *Applied Systems Analysis*. New York, NY.: McGraw-Hill Publishing Company.
- Federal Service Impasses Panel. 1997, November 12. Case No. 97 FSIP 88. *Combined Source Set 1 - Federal Service Impasses Panel Decisions*.
- Kim, S.-H., and Nelson, B. L. 2006. Selecting the Best System. in S. G. Henderson, B. L. Nelson, *Handbook in OR & MS*, 13: 501-535. Elsevier B.V.
- Law, A. M. 2007. *Simulation Modeling & Analysis*. 4th Edition. New York, NY.: McGraw-Hill.
- Levien, A. J. 2010. "Restructuring Depot Maintenance Occupational Series to Improve Flexibility." Masters Graduate Research Project. Department of Operational Analysis, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio.
- Little, J. D. 2004. "Models and Managers: The Concept of Decision Calculus." *Management Science*, 50 (12_supplement): 1841-1853.

- Nelson, B. L., Swann, J., Goldsman, D., and Song, W. (2001). "Simple Procedures for Selecting the Best Simulated System When the Number of Alternatives is Large". *Operations Research*, 49 (6): 950-963.
- Ogden Air Logistics Center. 2012. *Multi-Trade Demonstration Project*. Hill Air Force Base, Utah: Ogden Air Logistics Center Acquisition Cost Division.
- Park, P. S. 1991. "The examination of worker cross-training in a dual resource constrained job." *European Journal of Operational Research*, 52(3): 291-299.
- Slay, F. M., T. C. Bachman, R. C. Kline, T. J. O'Malley, and F. L. Eichorn. 1996. "Optimizing Spares Support: The Aircraft Sustainability Model". Report no. LMI-AF501MR1. National Technical Information Center: AD-A320 502/8.
- Ysebaert, S. C. 2011. "An Analytical Approach To Low Observable Maintenance Practices Using Simulation and Marginal Analysis." In *Proceedings of the 2011 Winter Simulation Conference*, edited by S. Jain, R.R. Creasey, J. Himmelspace, K.P. White, and M. Fu, 2530-2539, Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

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